PROBING PARSEC-SCALE JETS

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OVERVIEW

COLLIMATED RELATIVISTIC FLOWS

Accretion,$\mathbf{J} \Longrightarrow$ disks,energy $\Longrightarrow$ fast jets:

- pulsars
- Galactic microquasars
- γ-ray bursters
- AGN

Smooth flows uninteresting; (time-varying) structure makes flow visible, provides probe:

- changing gross morphology
- propagating internal structures

Parsec-scale flows of AGN evolve with τ_{gs}, and are spatially interesting. (NB. Recent pulsar results: Crab/Vela.)

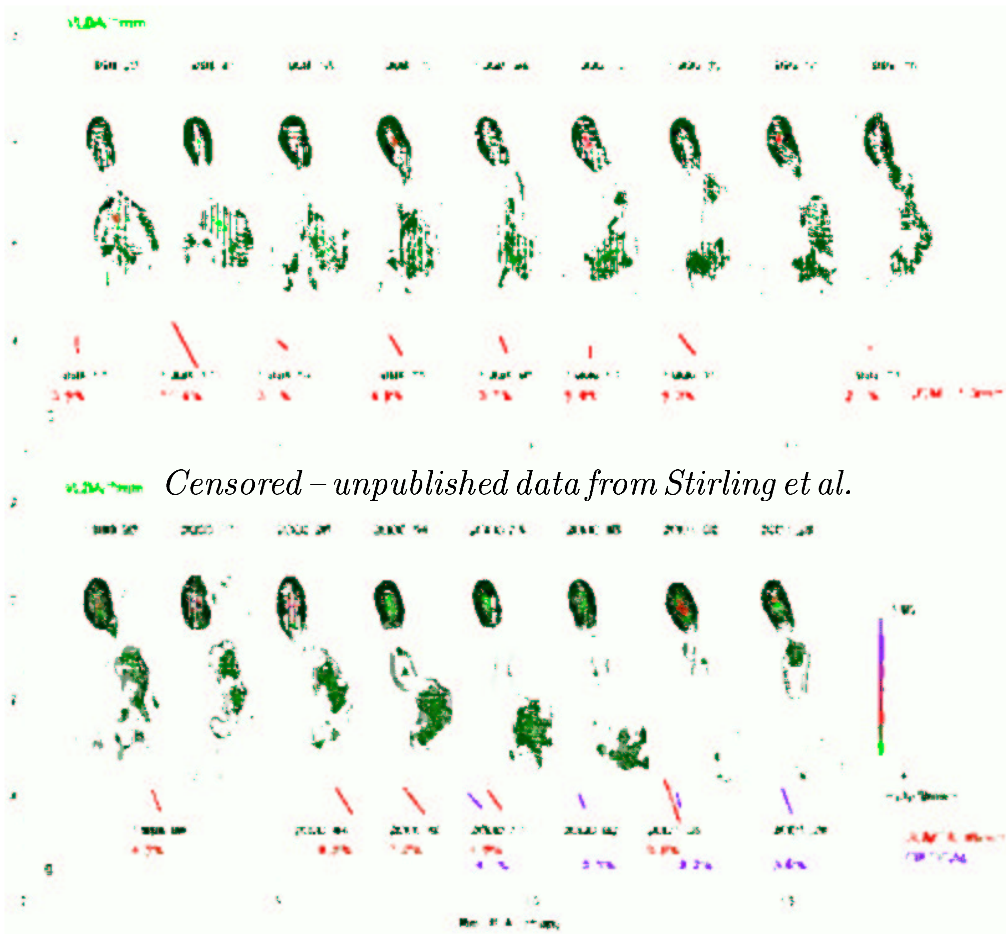
EXAMPLES

- **Precessing nozzle of BL Lac (Stirling et al.)**

  VLBA structural orientation tracks (variable) JCMT polarization orientation $\Rightarrow$ straight (wiggle-less) but precessing jet. [$\sim 17^\circ$ semi-angle observed, $\sim 3^\circ$ semi-angle inferred, over 2.5 years.]

- Evolving oblique structures of BL Lac (Aller et al.)

- Internal structure of M 87

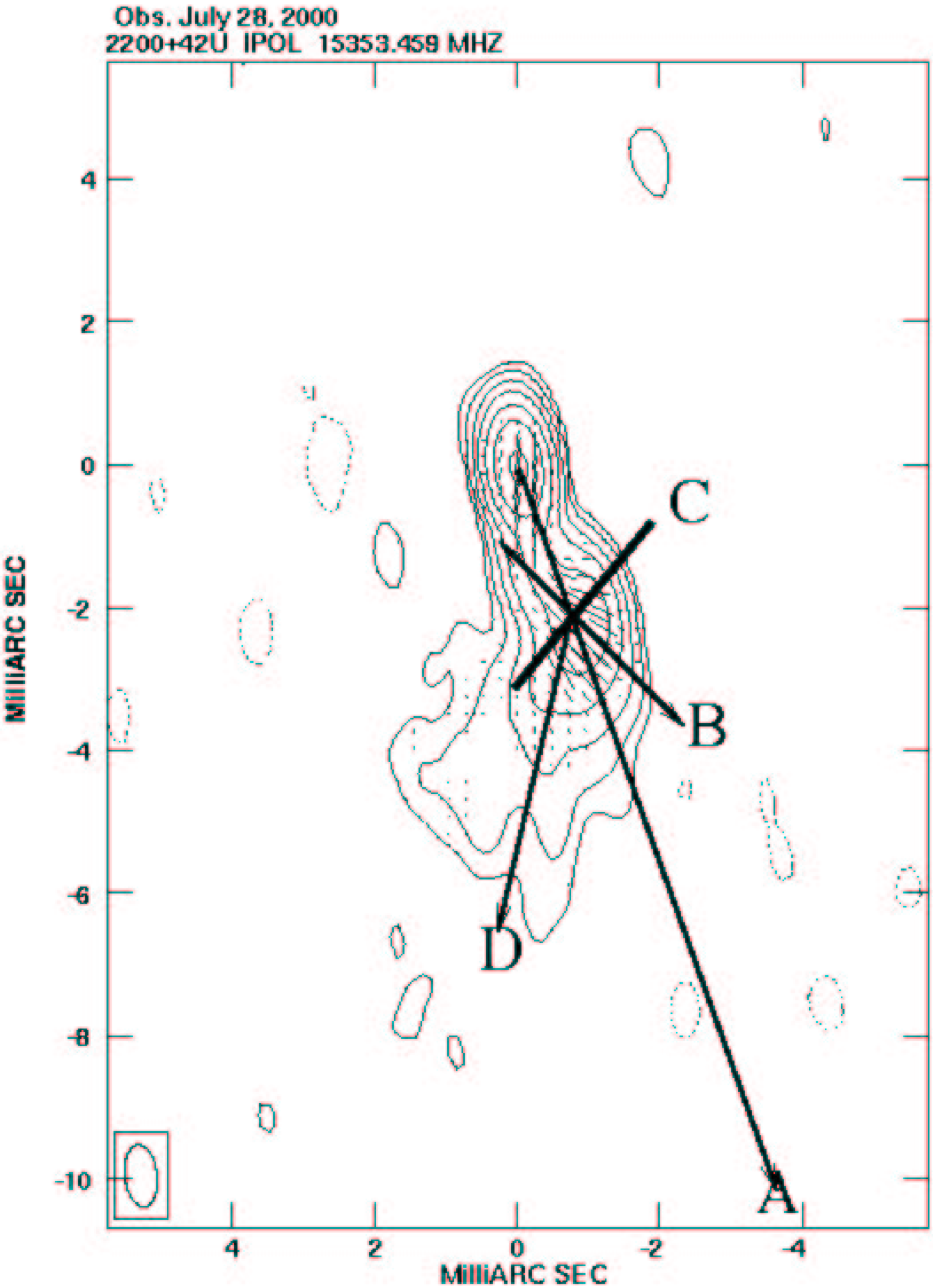


Censored – unpublished data from Stirling et al.

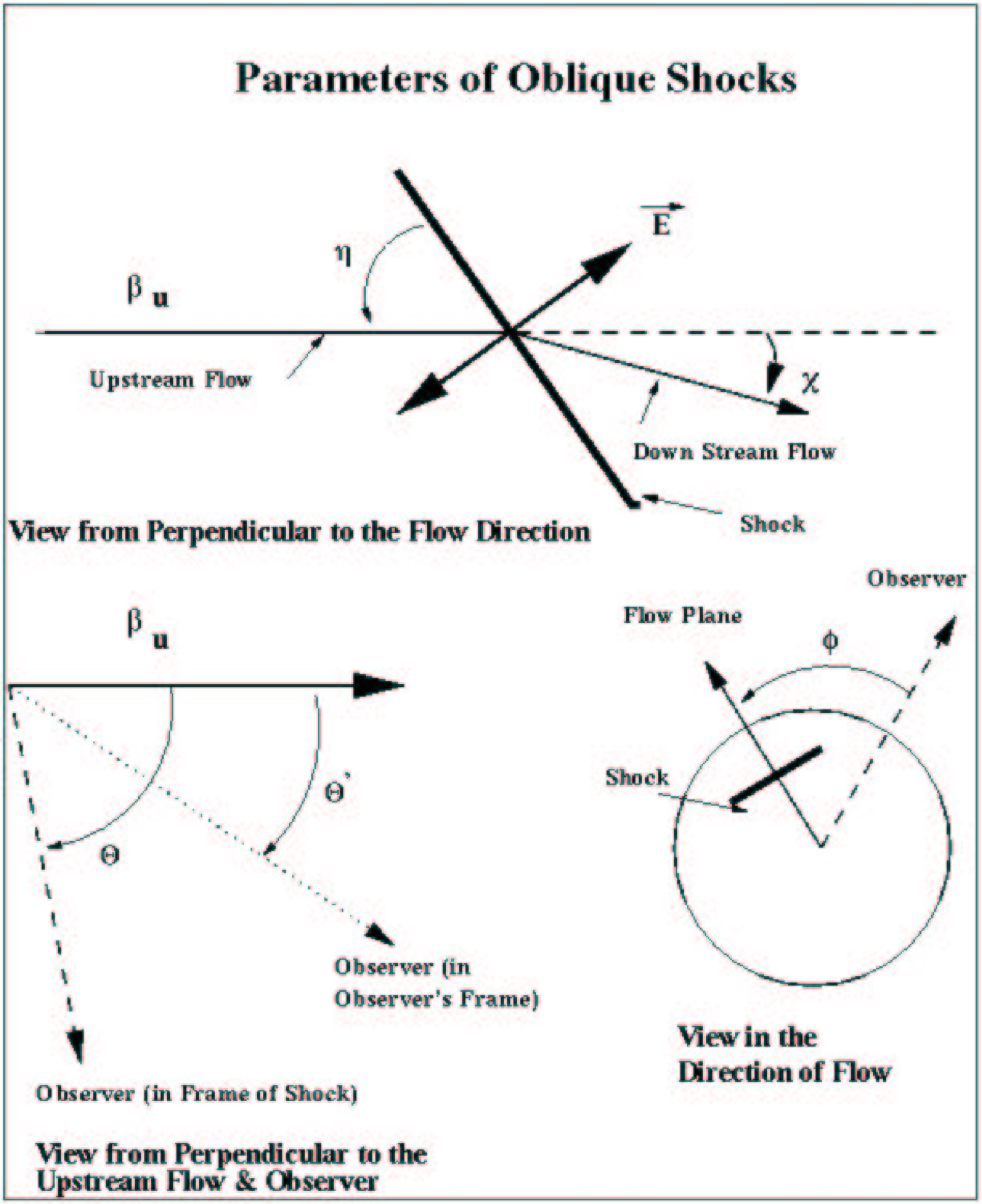
EXAMPLES

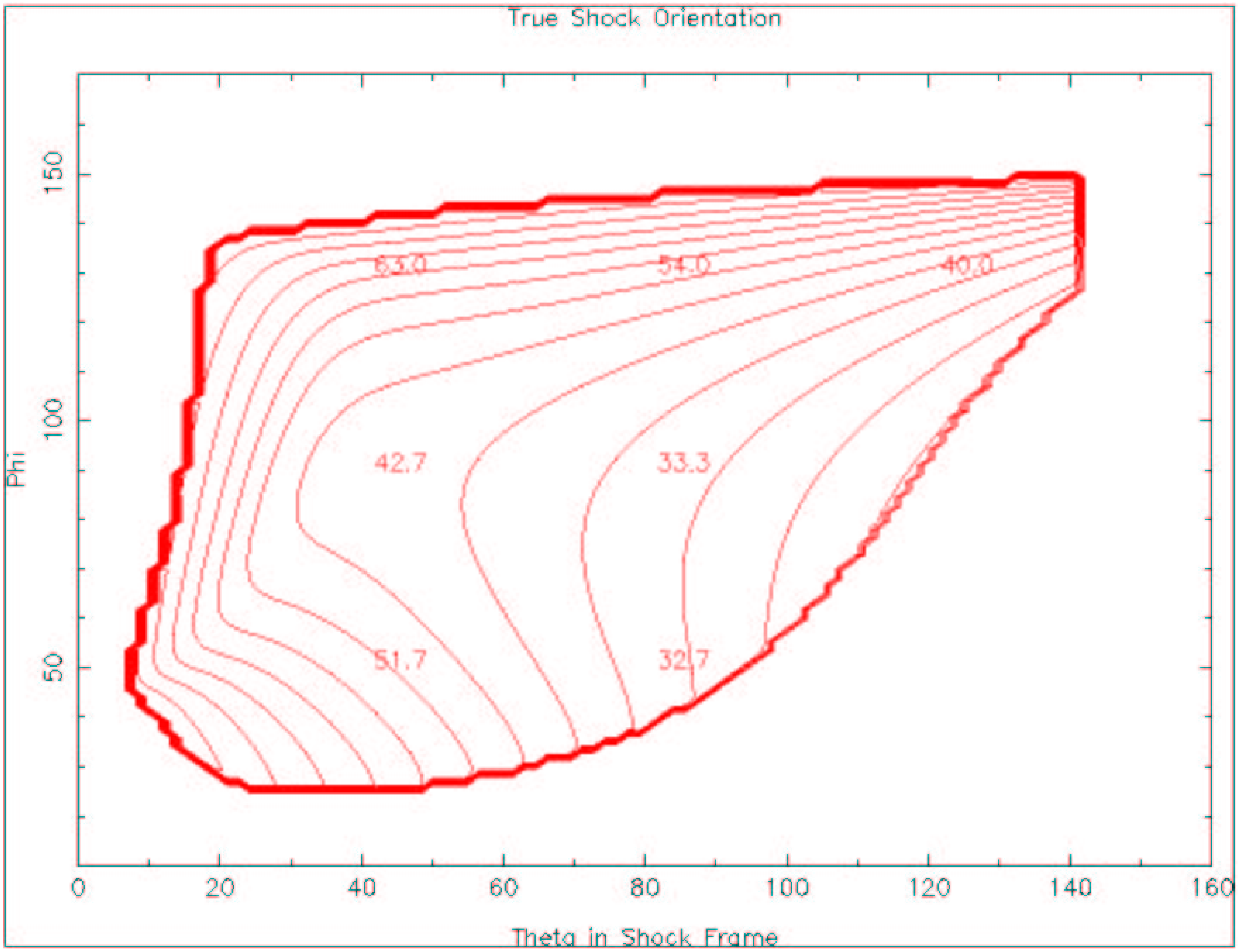
- Precessing nozzle of BL Lac (Stirling et al.)
- **Evolving oblique structures of BL Lac (Aller et al.)**

  $\eta(\theta, \phi)$ that will produce a 25% polarized component at an EVPA of 30° to the initial flow direction.
- Internal structure of M 87



Obs. July 28, 2000
2200+42U IPOL 15353.459 MHZ
MilliARC SEC
MilliARC SEC
4
2
0
-2
-4
-6
-8
-10
4
2
0
-2
-4
A
B
C
D

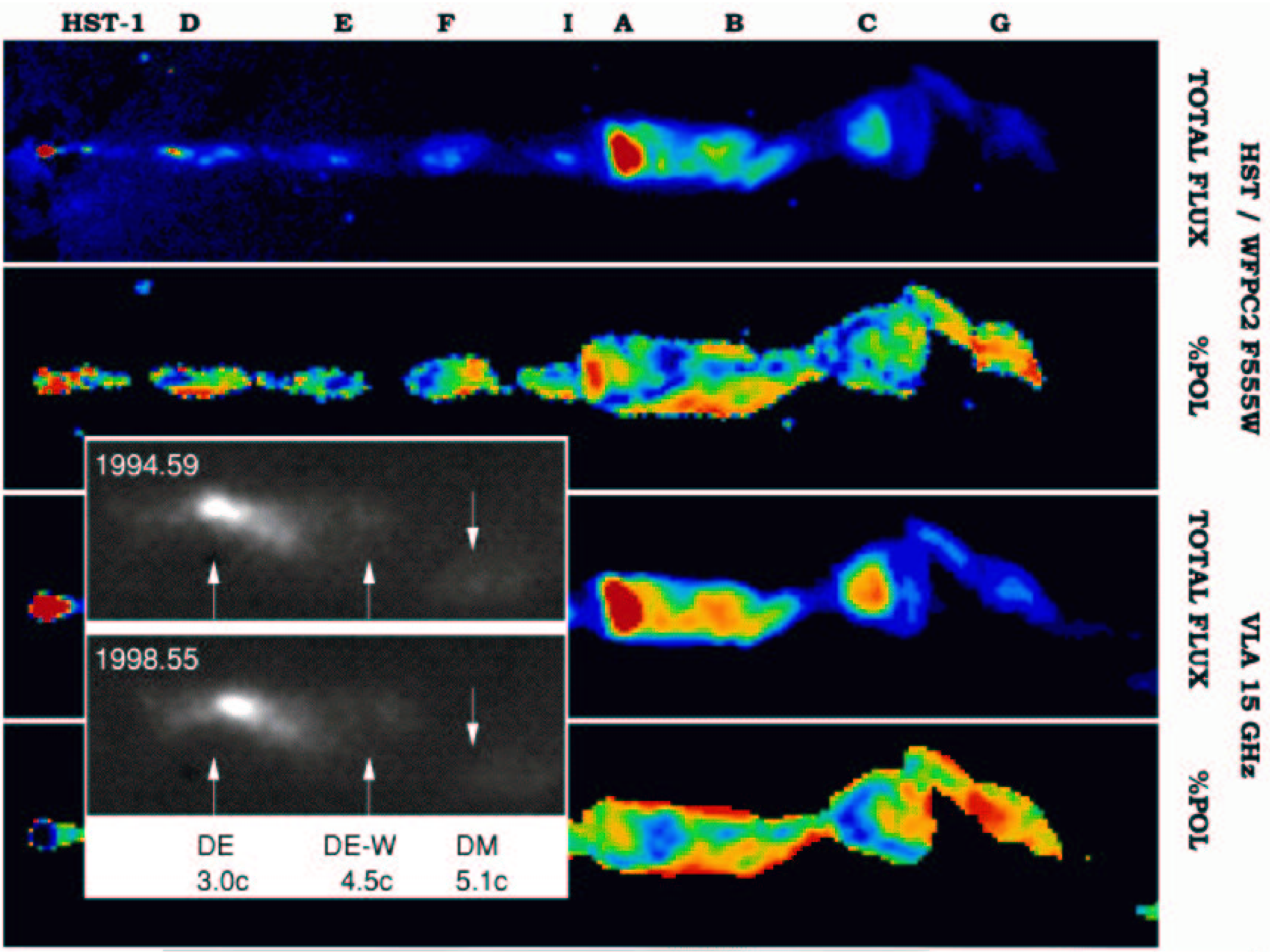

Parameters of Oblique Shocks
E
η
β u
Upstream Flow
χ
Down Stream Flow
Shock
View from Perpendicular to the Flow Direction
Observer
Flow Plane
φ
β u
Θ'
Θ
Shock
Observer (in
Observer's Frame)
View in the
Direction of Flow
Observer (in Frame of Shock)
View from Perpendicular to the
Upstream Flow & Observer



True Shock Orientation
Phi
Theta in Shock Frame
150
100
50
0
20
40
60
80
100
120
140
160
63.0
54.0
40.0
42.7
33.3
51.7
32.7

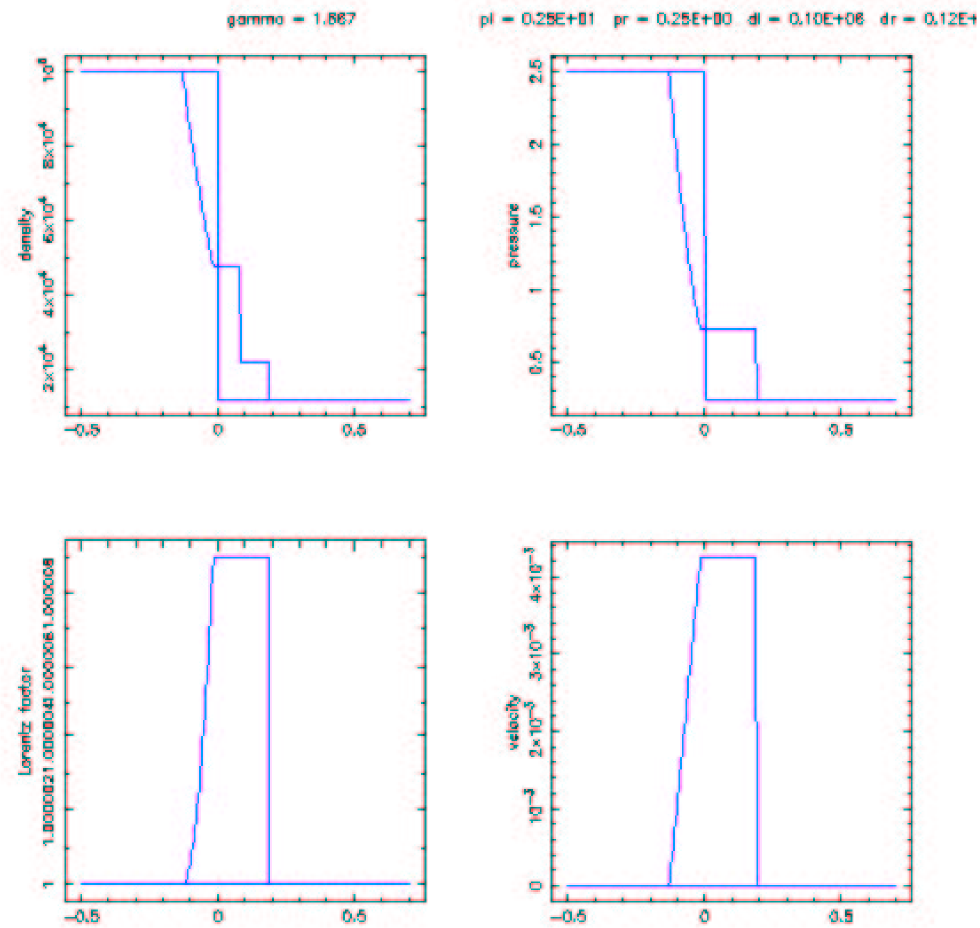
EXAMPLES

- Precessing nozzle of BL Lac (Stirling et al.)
- Evolving oblique structures of BL Lac (Aller et al.)
- **Internal structure of M 87**

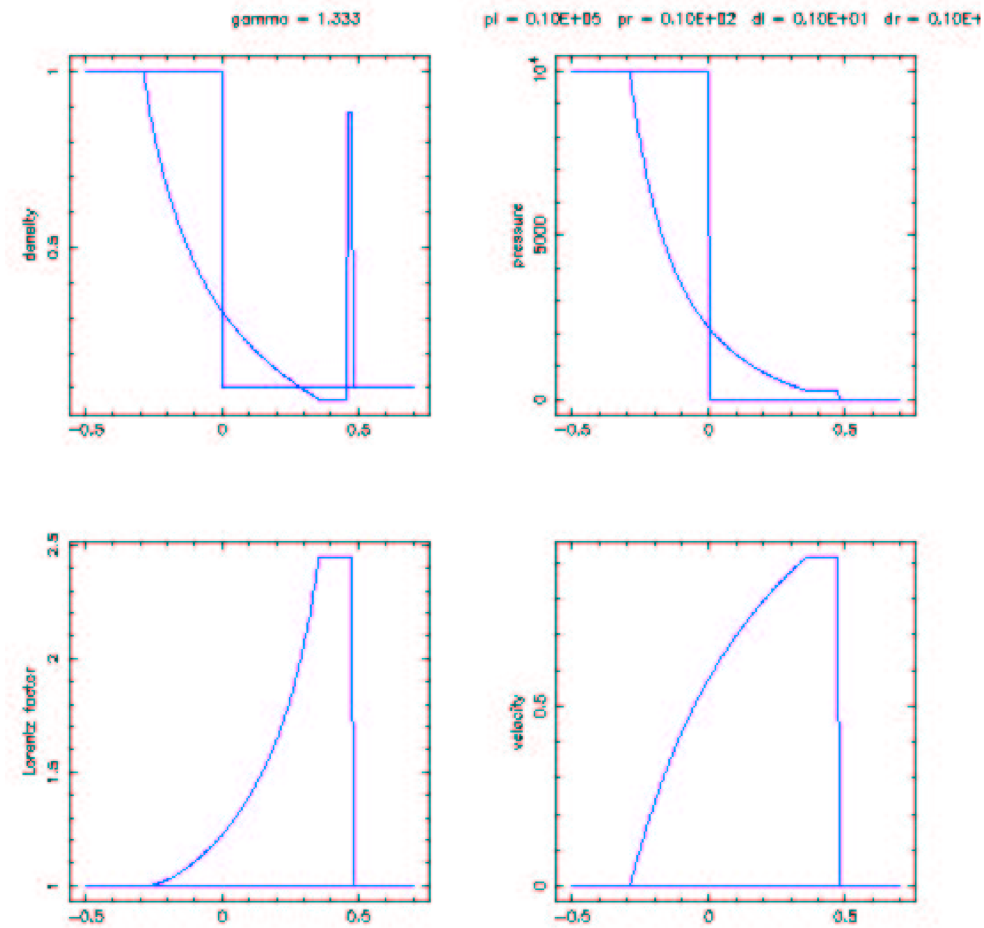

HST-1 D E F I A B C G
HST / WFPC2 F555W
TOTAL FLUX
%POL
VLA 15 GHz
TOTAL FLUX
%POL
1994.59
1998.55
DE
3.0c
DE-W
4.5c
DM
5.1c

ROLE OF RELATIVISTIC CFD

- Radiation MHD?
  a. Radiation impacts dynamics on sub-parsec scale.
  b. $\mathbf{B}$ is uncertain, with significant $\delta\mathbf{B}$; small errors in latter will lead to spurious predicted polarization; still no knowledge of CR distribution for mapping.
- Relativistic CFD is different/necessary:
  a. No limit to shock thinness/strength
  b. Manifestly different global dynamics (Rosen et al.)
- NB. Interface with analytic work (PEH) and observation.



Non-relativistic shock tube.



Relativistic shock tube – qualitatively different!

GOALS OF RELATIVISTIC CFD

- Integrity of macroscopically precessed flow – internal structures
- Formation and evolution of oblique internal shocks
- Formation and evolution of normal-mode structures

THE CFD TECHNIQUE

Nonrelativistic Euler Equations in 1-D

$$\frac{\partial}{\partial t}\rho + \frac{\partial}{\partial x}\rho v = 0$$
$$\frac{\partial}{\partial t}m + \frac{\partial}{\partial x}\left(mv + p\right) = 0$$
$$\frac{\partial}{\partial t}e_t + \frac{\partial}{\partial x}\left(e_t + p\right)v = 0$$

where ρ – mass density, $m = \rho v$ – momentum, and e_t – total energy are conserved quantities.

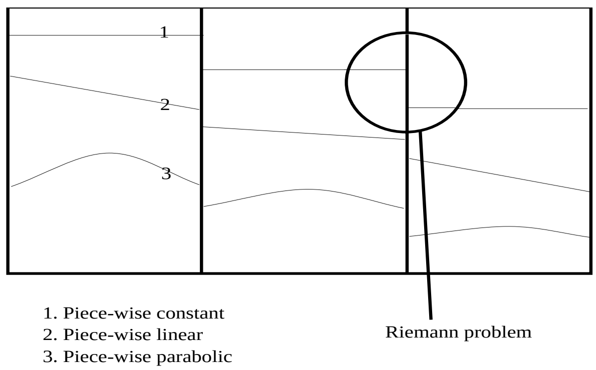
Relativistic Euler Equations in 1-D

$$\frac{\partial}{\partial t}R + \frac{\partial}{\partial x}Rv = 0$$
$$\frac{\partial}{\partial t}M + \frac{\partial}{\partial x}\left(Mv + p\right) = 0$$
$$\frac{\partial}{\partial t}E + \frac{\partial}{\partial x}\left(E + p\right)v = 0$$

where $R = \gamma n$ – mass density, $M = \gamma^2\left(e + p\right)v$ – momentum, $E = \gamma^2\left(e + p\right) - p$ – total energy in lab frame, are conserved quantities.

$c = 1$, Lorentz factor: $\gamma = \left(1 - v^2\right)^{-1/2}$; $R = \gamma n$, $M = \gamma^2\left(e + p\right)v$, $E = \gamma^2\left(e + p\right) - p$.

Discretize flow domain, yielding a set of Riemann problems.



Use conserved variables:

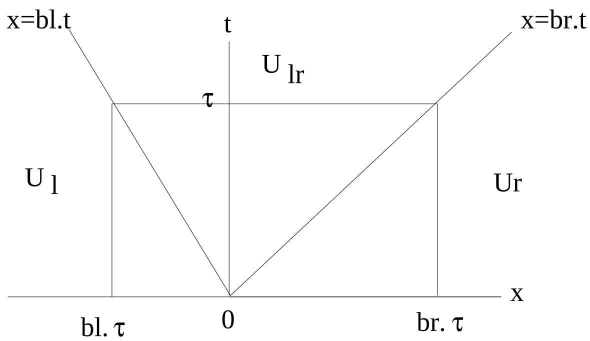
$$U_t + F\left(U\right)_x = 0, \quad U = \{R, M, E\}$$

$$U_i^{n+1} = U_i^n - \frac{\Delta t}{\Delta x}\left(G_{i+1/2}^n - G_{i-1/2}^n\right)$$

$G_{i+1/2}^n = G\left(U_i^n, U_{i+1}^n\right)$, the flux between grid cells.

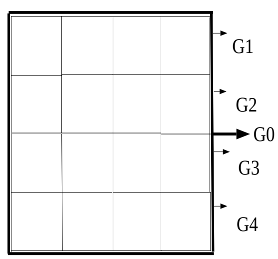
Compute flux from solution to Riemann problem at each interface. Adopt Harten, Lax, van Leer & Einfeldt's approximation: 3 constant states + 2 linear discontinuities.

$$U\left(x,t;U_l,U_r\right)=\begin{cases}U_l, & \text{for } x<b_l t;\\ U_{lr} & \text{for } b_l t\le x\le b_r t;\\ U_r & \text{for } x>b_r t\end{cases}$$



Adaptive Mesh Refinement

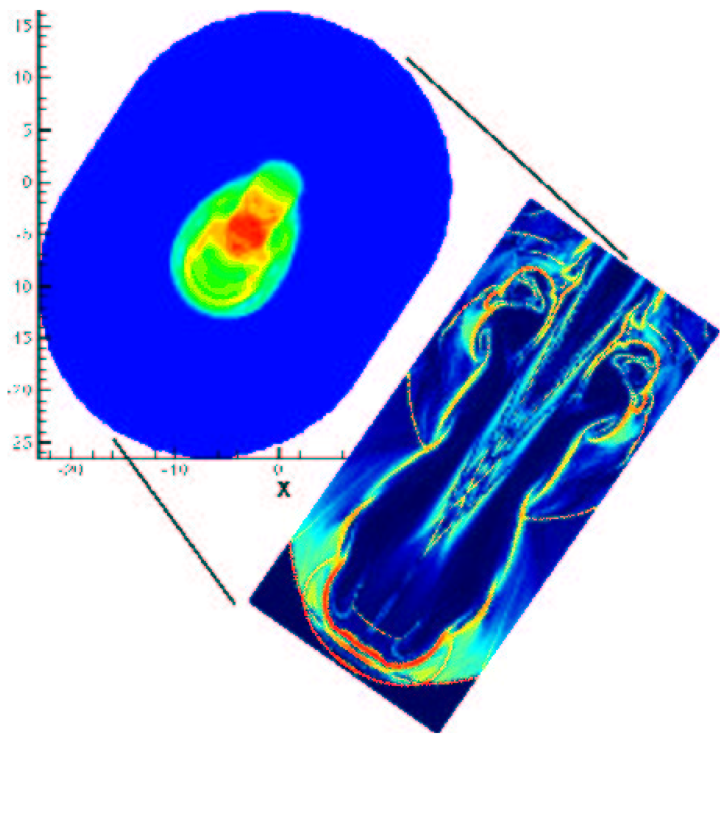
- ⋆ Flag cells for refinement using $\nabla\rho$, shear...
- ⋆ Cluster cells into rectangular, properly nested domains
- ⋆ Interpolate or Transfer solution from coarse to fine grids
- ⋆ Advance fine solution in N steps of size $\Delta T/N$, using spatially/temporally interpolated values from coarse level in boundary, interleaving
- ⋆ Project fine solution upwards
- ⋆ Fix-up non-conservation – optional



THE ATTAINABLE –I – COMPARISON WTH DATA

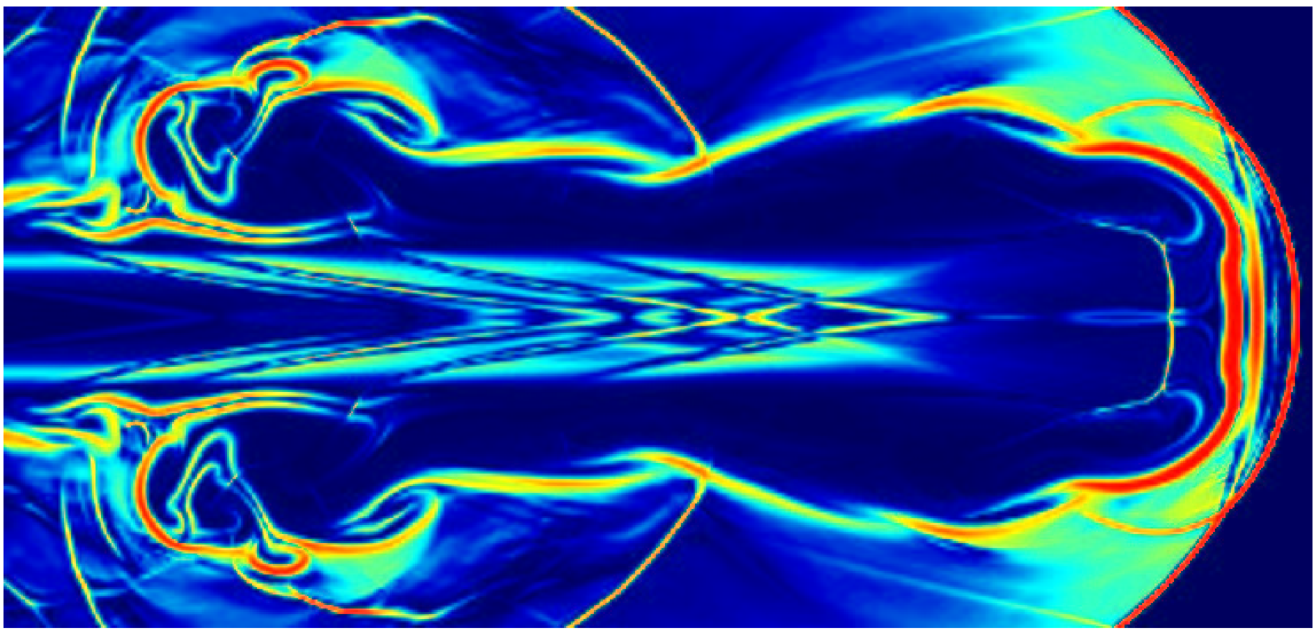
Flux maps of simulated 2D relativistic jets by C. M. Swift:

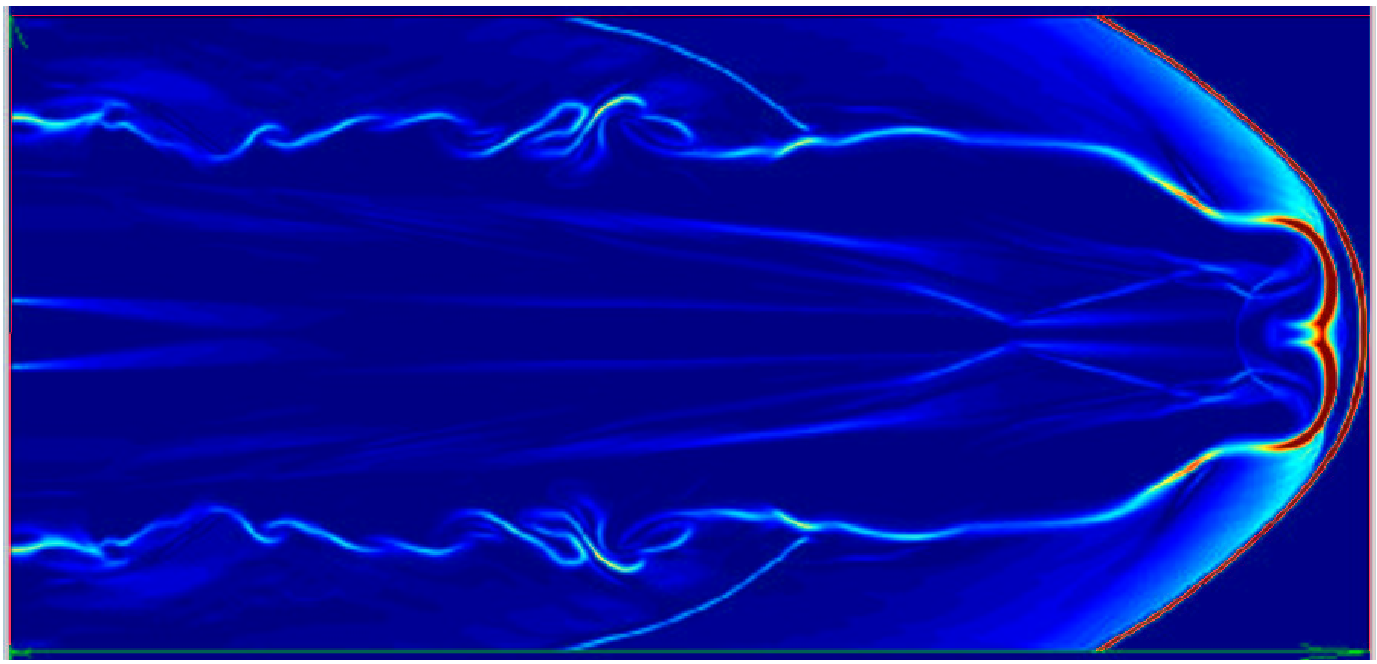
- mildly relativistic jets show fairly complex radio structure, reflective of their internal hydrodynamics
- highly relativistic jets show little structure from any angle of view, at any epoch



THE ATTAINABLE – II – COMPUTATIONAL RESOURCES

- Slice of 2D run, c1994: desktop workstation.
- Slice of 3D run, 2003: 16 nodes of Linux cluster.

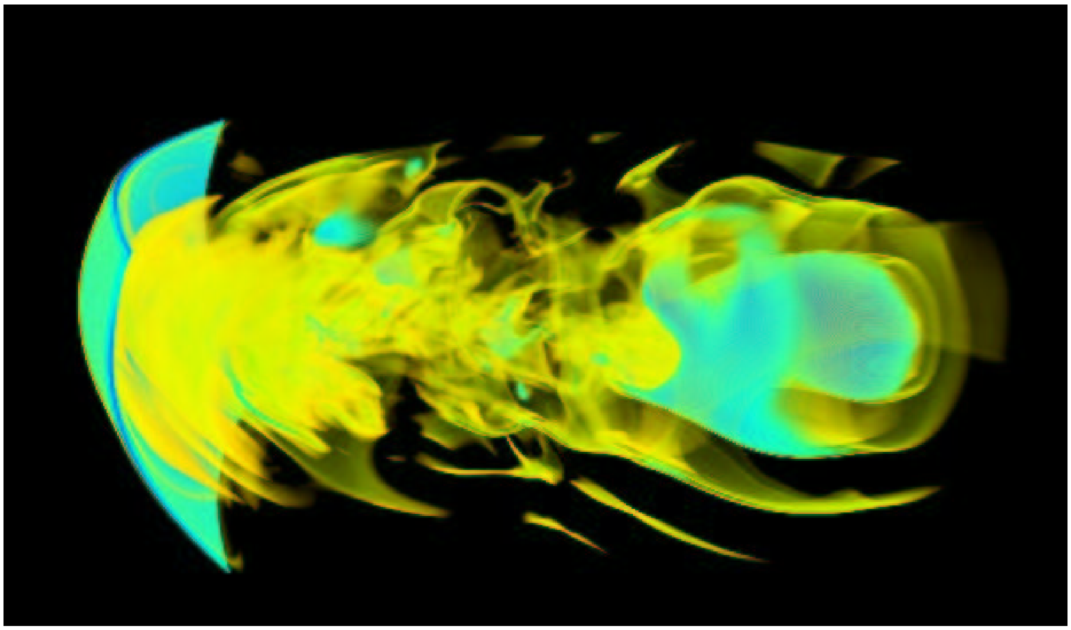


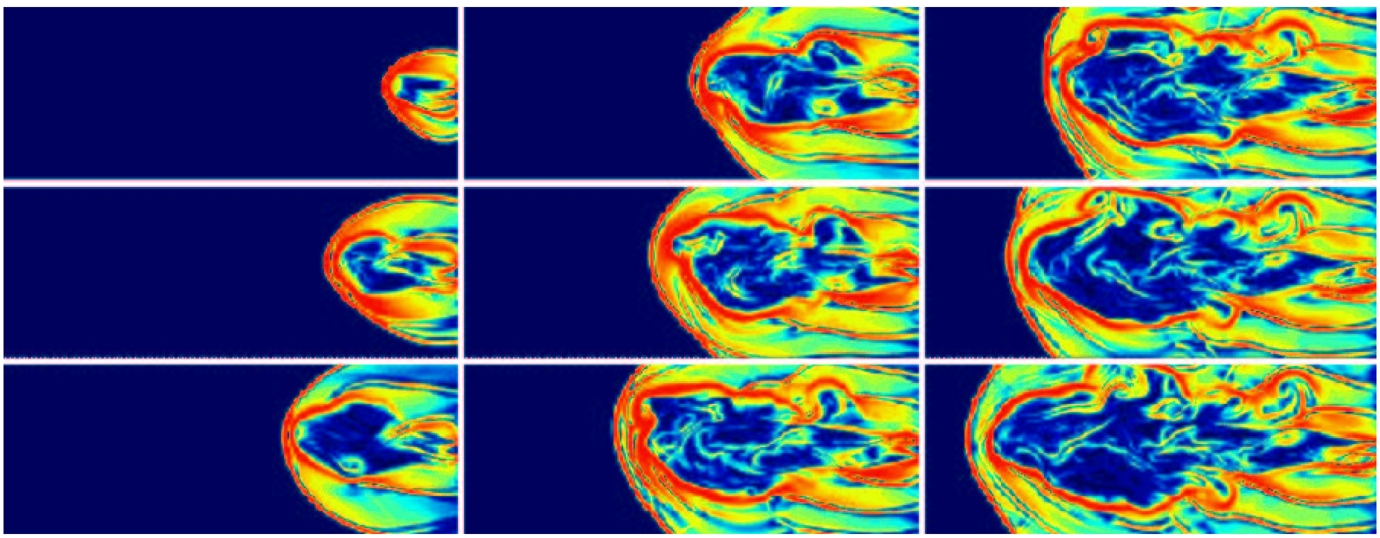


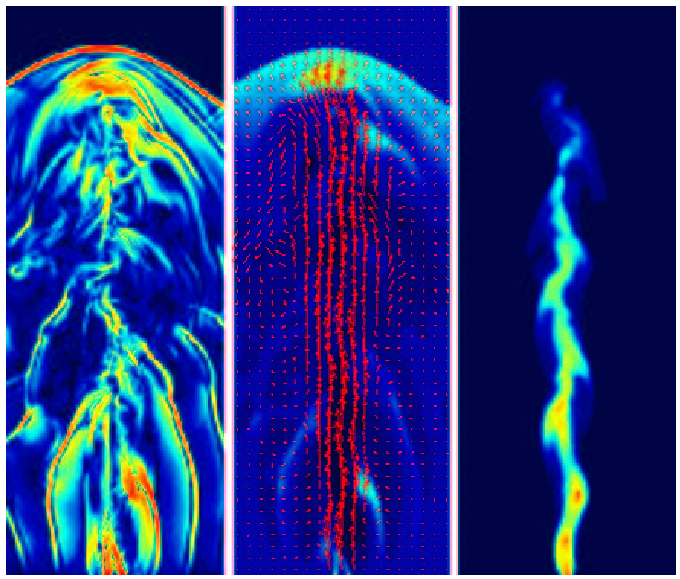
RESULTS

Integrity of macroscopically precessed flow – internal structures

Retain integrity, with modest reduction in Lorentz factor and momentum flux, for almost 50 jet-radii, but thereafter disrupted. Flow is approximately ballistic. Convolution of rest frame emissivity and Doppler boost leads to a core-jet like structure for any observer close to the inflow axis.



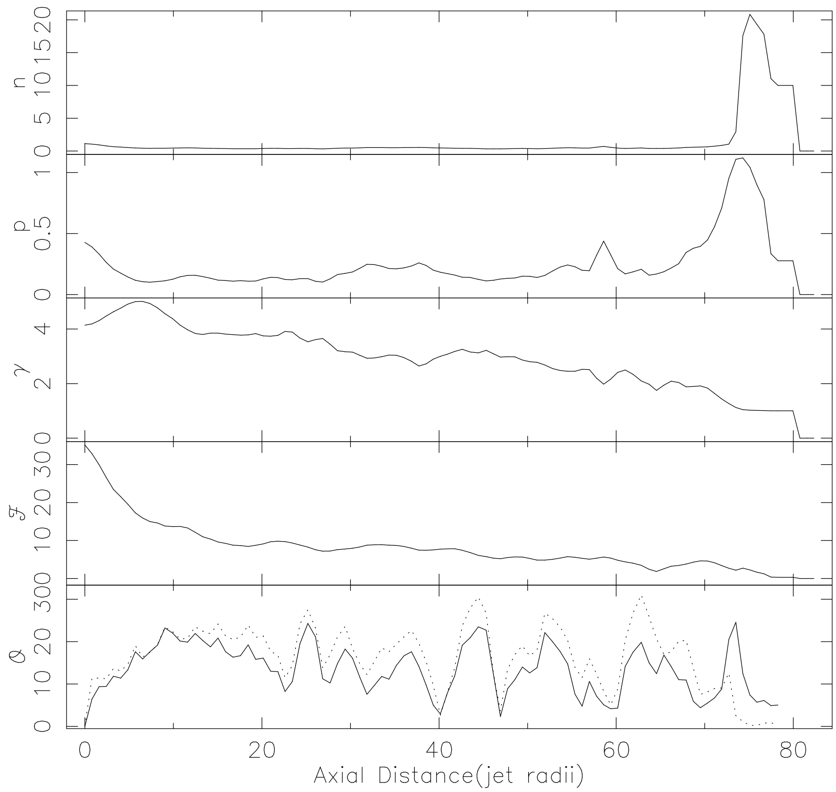




L. Schlieren pressure

M. pressure/3-velocities

R. Lorentz factor

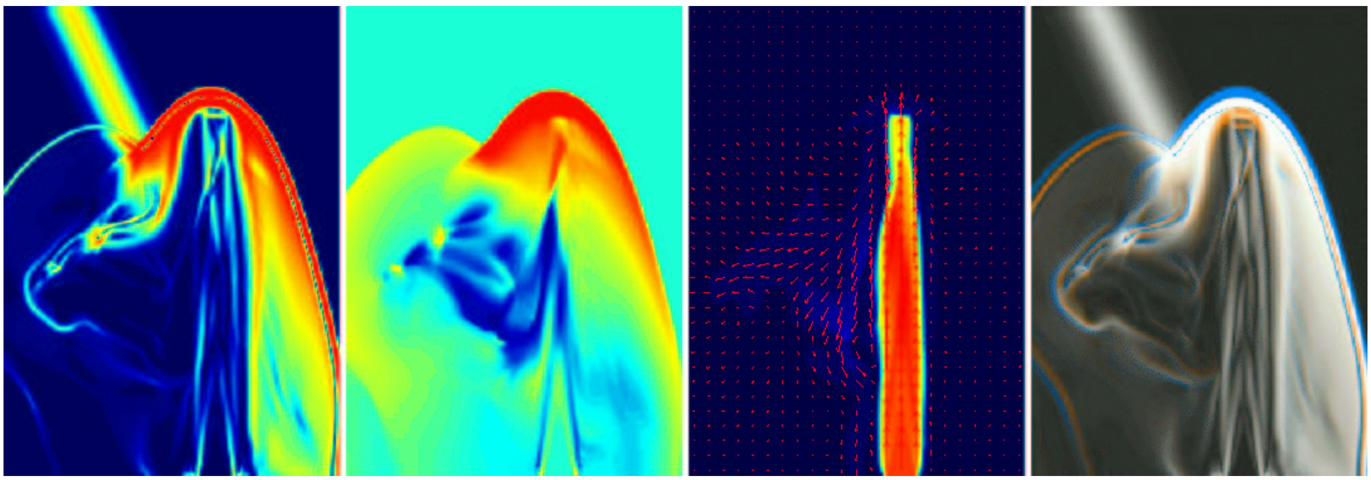


B. — velocity wrt spine; - - - axis wrt spine.

Formation and evolution of oblique internal shocks

Impinging on an oblique density gradient, jet exhibits rotating Mach disk. Flow bent via a potentially strong, oblique internal shock. Significantly enhanced emission may be associated with the oblique shocks. Cocoon may form marginally relativistic flow *orthogonal* to the jet.

Unboosted flux enhancement $\sim 2.5 - 3.5$.

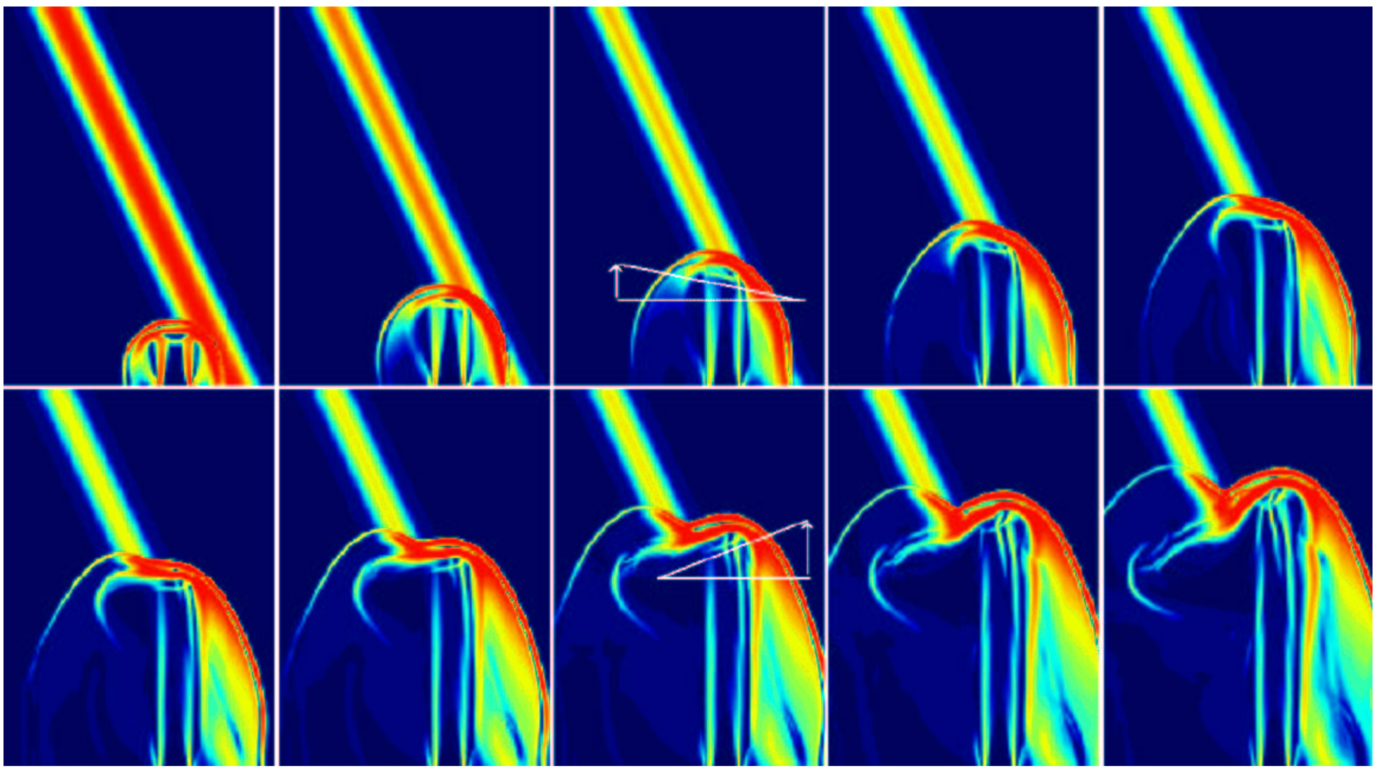


L. Schlieren density

M. pressure

M. Lorentz factor/3-velocities

R. displacement

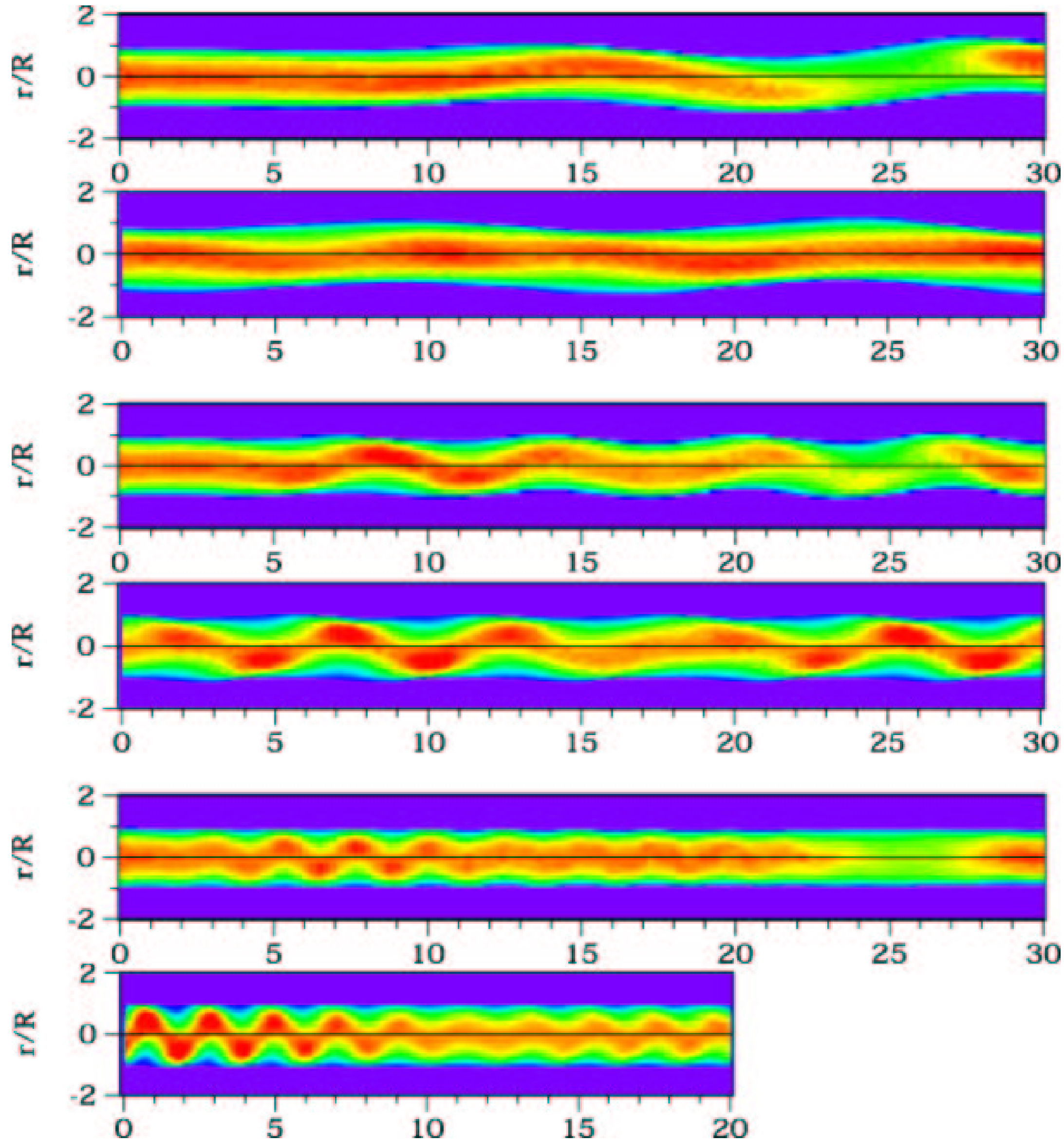


Formation and evolution of normal-mode structures

In both 2D and 3D flows, internal structures are fully understandable in terms of the structure and growth or damping of the normal Fourier modes and the coupling to the perturbations that might drive them.

- CFD validates use of linear stability analysis for macroscopic perturbations
- stability analysis enables interpretation of CFD
- identification of modes and their evolution probes flow state – e.g., internal and external sound speeds
- stationary/propagating structures arise naturally, not by fiat
- potential to explain observed quasi-periodic activity

Example: $\gamma = 2.5$, 3 driving frequencies, comparison of $\int p^2 ds$ for U.) simulation, L.) stability analysis (PEH).


r/R
2
0
-2
0
5
10
15
20
25
30

Aside:

With Brandon Kelly, cross-wavelet analysis of UMRAO data:

$$\psi_{\mathrm{Morlet}} = e^{-ik_\psi t} e^{-|t^2|/2}$$

$$\tilde{f}\left(l, t'\right) = \int_{\mathbf{R}} f\left(t\right) \psi^*_{lt'}\left(t\right) dt$$

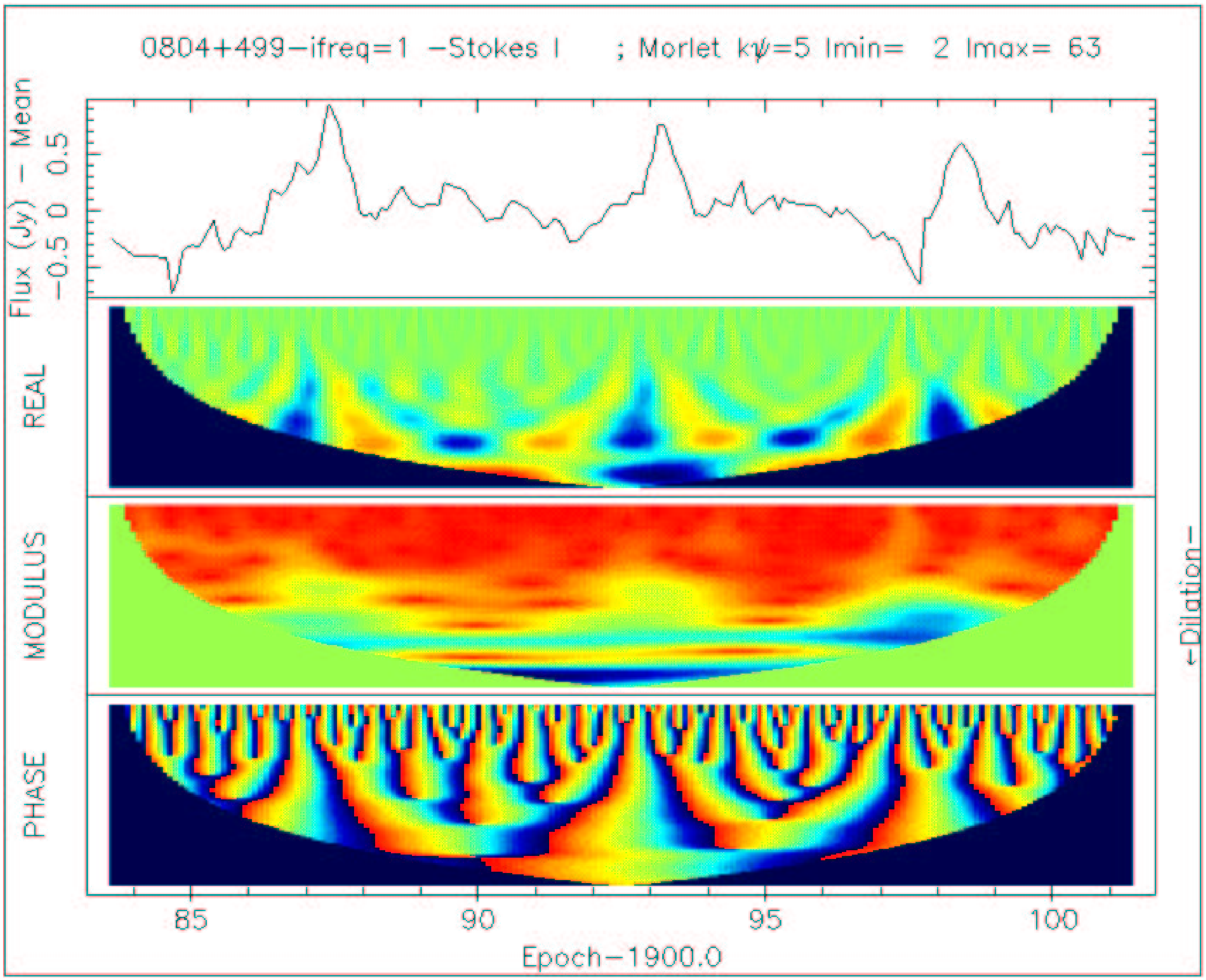
$$\psi_{lt'}\left(t\right) = l^{-1/2} \psi \left[\frac{t - t'}{l}\right], \; l \in \mathbf{R}^+, \; t \in \mathbf{R}$$

$$\int_{\mathbf{R}} \psi(t) dt = 0$$

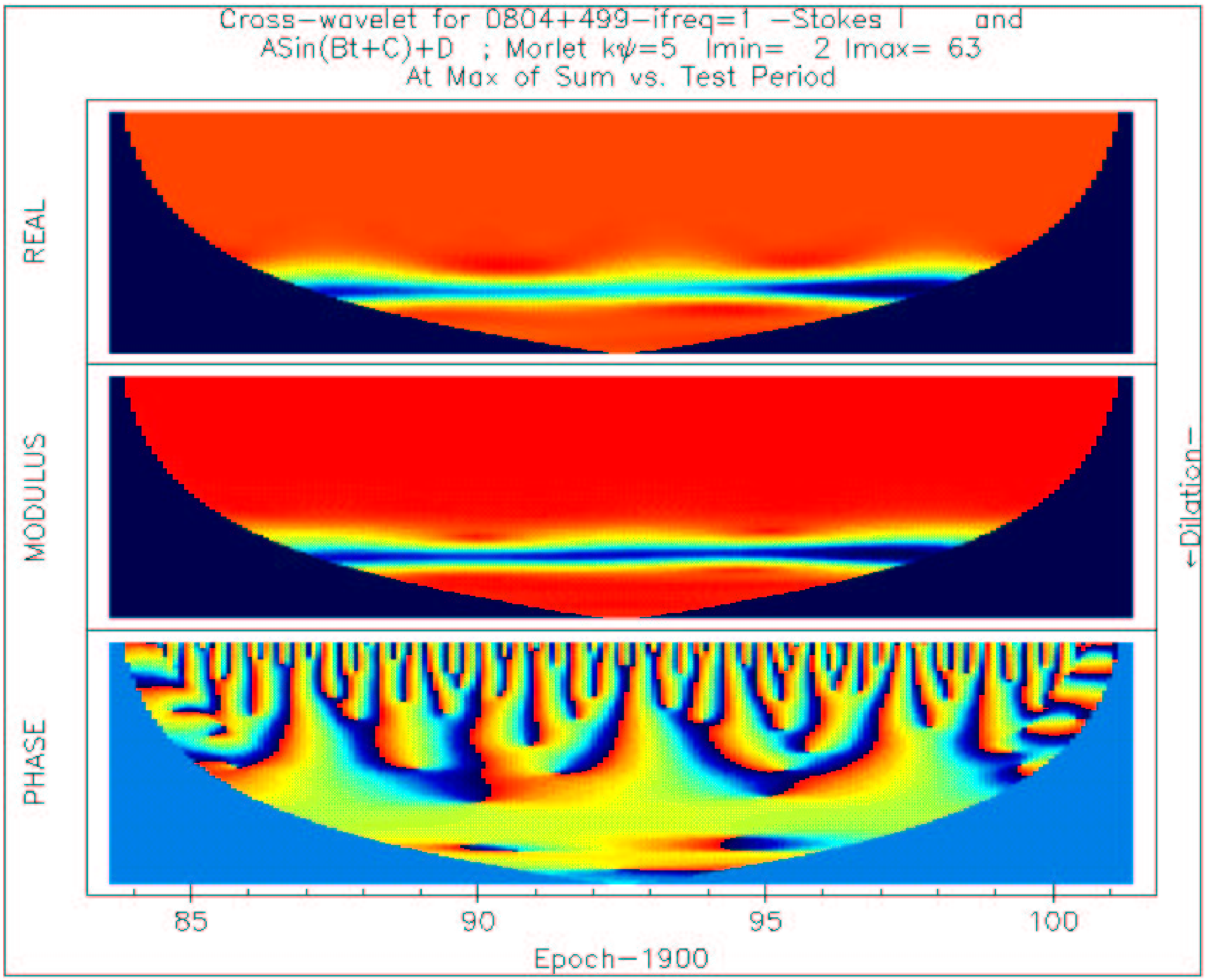
$$\boxed{\tilde{f}_c\left(l, t'\right) = \tilde{f}_a\left(l, t'\right) \cdot \tilde{f}^*_m\left(l, t'\right)}$$

Major effort to evaluate confidence level for quasiperiodic signal.

Finds quasi-periodic behavior is common – manifestation of propagating normal mode structures?



0804+499–ifreq=1 –Stokes I ; Morlet kψ=5 lmin= 2 lmax= 63
Flux (Jy) – Mean
0.5
0
−0.5
REAL
MODULUS
PHASE
←Dilation–
85
90
95
100
Epoch−1900.0



Cross-wavelet for 0804+499-ifreq=1 -Stokes I and
ASin(Bt+C)+D ; Morlet kψ=5 lmin= 2 lmax= 63
At Max of Sum vs. Test Period
REAL
MODULUS
PHASE
←Dilation–
85
90
95
100
Epoch–1900

SUMMARY

Simulation and analytic study of relativistic flows has yielded valuable insight into their behavior, shedding light on how structures form and evolve.

In conjunction with data this is starting to probe the kinematic and internal states of jet and ambient medium.

FUTURE

- high resolution 3D with ambient structures/gradients
- $\mathbf{B}$ with significant $\delta\mathbf{B}$